

RELATIVISTIC OUTFLOW MAGNETICALLY DRIVEN BY BLACK HOLE ROTATION

SHINJI KOIDE

Faculty of Engineering, Toyama University, 3190 Gofuku, Toyama 930-8555, Japan; koidesin@eng.toyama-u.ac.jp

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ABSTRACT

In the universe, several kinds of relativistic jets have been discovered, and it is believed that they are formed by violent phenomena near black holes. Despite the advancement of observations and black hole physics, their acceleration mechanisms are still not understood. Here, using numerical simulations, we show that the relativistic outflow is formed spontaneously by the magnetic field very near the rapidly rotating black hole. Previous simulations showed electromagnetic energy emission and nonrelativistic outflow formation in the black hole magnetosphere, but actual relativistic outflows have not yet been obtained. The present simulation shows that magnetic flux tubes, oblique to the rotation axis across the black hole horizon, are twisted into the shape of screws and propel plasma around the black hole to the relativistic regime.

Subject headings: black hole physics — magnetic fields — methods: numerical — MHD — plasmas — relativity

On-line material: color figure

In the universe, relativistic jets are observed in active galactic nuclei (Biretta, Sparks, & Macchetto 1999), quasars (Pearson & Zensus 1987), objects called microquasars in our Galaxy (Mirabel & Rodriguez 1994; Tingay et al. 1995), and central objects of gamma-ray bursts (GRBs; Kulkarni et al. 1999). These relativistic jets are thought to be ejected as a result of violent phenomena around black holes. Among a number of theories of relativistic jet formation around the black hole, the magnetically driven mechanism is the most attractive and becomes noticeable because it can explain not only the acceleration of the jet but also its collimation, and it explains some features of recent observations (Junor, Biretta, & Livio 1999; Mirabel & Rodriguez 1998; Mészáros & Rees 1997). However, the theory of magnetically driven relativistic jet formation lacks an important piece: a distinct, *self-consistent* solution without artificial assumptions about plasma dynamics. We performed general relativistic magnetohydrodynamic (MHD) numerical simulations of a magnetosphere around a rotating (Kerr) black hole in an initially vertical, uniform magnetic field (Koide, Shibata, & Kudoh 1998, 1999; Koide et al. 2000, 2002; Koide 2003). In the cases with disks around the black holes, the jets are formed from the accretion disks, but the jet velocity is subrelativistic, $v_{\text{jet}} < 0.5c$, where c is the light speed (Koide et al. 1998, 1999, 2000). With respect to the cases without disks, no outflow was found, while the magnetic energy propagates outward powerfully along the magnetic field lines (Koide et al. 2002; Koide 2003). No self-consistent numerical solution of an actual relativistic outflow had been found until now. The static (self-inconsistent) theory suggests that the widely open magnetic flux tube (like a trumpet oblique to its rotational axis) accelerates the plasma much more effectively than does the uniform magnetic field (Takahashi et al. 1990). In this report, we show the results of a general relativistic MHD simulation of the spontaneous formation of the relativistic outflow around the rapidly rotating black hole with a radial magnetic field whose field lines are oblique to the rotational axis of the black hole (except for the rotation axis vicinity) and widely open.

To investigate the fundamental dynamics of the plasma and electromagnetic field around the Kerr black hole, we employ the general relativistic conservation laws of the particle number, momentum, and energy around the black hole (Koide et al. 2002; Koide 2003). We also use the general relativistic forms of Max-

well equations of the electromagnetic field around the Kerr black hole. In addition, we assume that the electric resistance is zero (ideal MHD condition). The rotational parameter $a = J/J_{\text{max}}$ is used to indicate the angular momentum of the black hole J , where J_{max} is the maximum angular momentum of the black hole with the mass M , $J_{\text{max}} = GM^2/c$ (G is the gravitation constant). In this Letter, we set $a = 0.99995$, which means that the black hole rotates almost maximally. To calculate the time evolution of the plasma and magnetic field around the black hole, we use a simplified total variation diminishing (TVD) difference scheme with a 3 + 1 formalism of the general relativistic MHD equations, in which spatial (three components) and time (one component) derivatives are completely separated (Koide 2003). We calculate the region around the black hole, $1.01r_H \leq r \leq 40r_H$, $0.01 \leq \theta \leq \pi/2$, where (r, θ, Φ) are the spherical laboratory coordinates, which are also called Boyer-Lindquist coordinates. Here r_H is the radius of the black hole boundary, which is called the horizon, $r_H = [1 + (1 - a^2)^{1/2}]r_s/2 = 0.505r_s$, where r_s is the Schwarzschild radius, $r_s = 2GM/c^2$. As an initial condition of the magnetic field around the Kerr black hole, we set the magnetic field of the magnetically charged (monopole) rotating black hole. We write the strength of the initial magnetic field at $R = r \sin \theta = r_s$, $z = r \cos \theta = 0$ by B_0 . The mass density of the plasma is initialized as $\rho = \rho_0(-3 \log \alpha)^5$, where $\rho_0 = 1.8 \times 10^{-2} B_0^2 / \mu_0 c^2$, μ_0 is the magnetic permeability in the vacuum, and α is the lapse function of the Kerr spacetime, which evaluates the gravitational redshift. The gas pressure is assumed in the hydrostatic quasi-equilibrium, in which far from the horizon the plasma is hydrostatic: $p = \rho_0 c^2 (-3 \log \alpha)^{6/18}$. The initial radial velocity of the plasma measured by the local observer, which is called the fiducial observer (FIDO) frame, is $v_r = -c(r/r_H)^{-6.86}$, and the initial angular momentum of the plasma is zero. This initial condition means that the plasma is at rest far from the horizon, while it falls with the speed of light at the horizon. Over the whole calculation region, the magnetic field energy is dominant compared with the thermal and rest-mass energy of the plasma.

Figure 1 shows the time evolution of the magnetic field and the poloidal velocity of the plasma of a system containing a radially strong magnetic field, thin plasma, and a rapidly rotating black hole. The azimuthal component of the magnetic field (B_ϕ) increases at $t = 10.7\tau_s$, where $\tau_s = c/r_s$ (Fig. 1b).

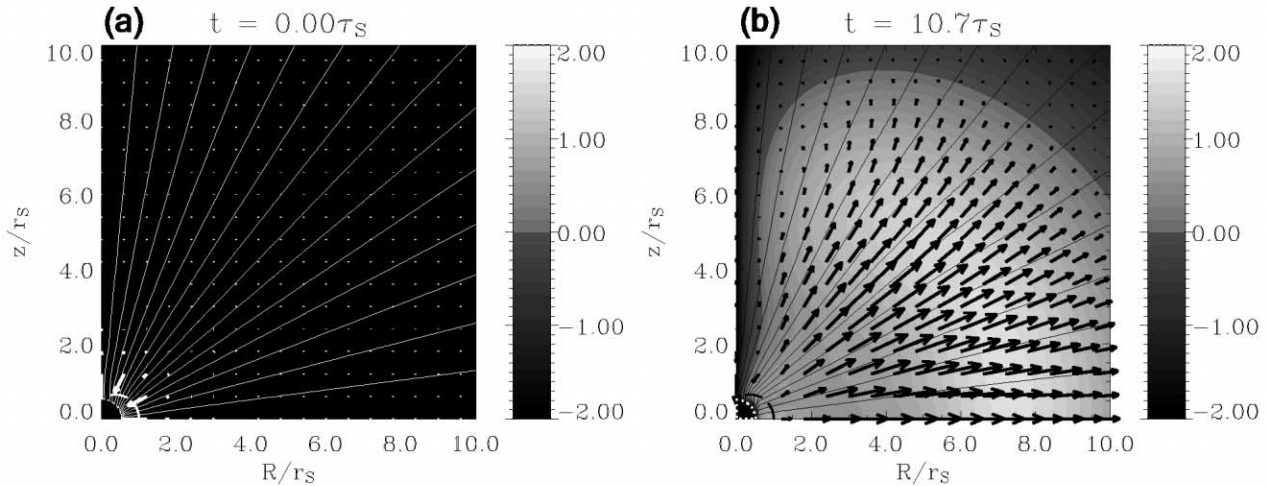


FIG. 1—Time evolution of the magnetic flux surface (lines), the plasma velocity (arrows), and $\log(B^2_0/\mu_0\rho c^2)$ (gray scale) at (a) $t = 0$ and (b) $t = 10.7\tau_s$. The black quarter-circle at the origin indicates the event horizon of the black hole. The dotted lines show the inner boundary of the calculation region at $r = 1.01r_H$. The dashed lines show the boundary of the ergosphere.

This is due to the general relativistic effect around the Kerr black hole. The rotation of the black hole causes the rotation of the space around the black hole. This effect is called the “frame-dragging” effect. The frame-dragging effect forms a special region called an ergosphere near the black hole, in which no material, energy, or information can propagate in the opposite direction of the black hole rotation. Hence, in the ergosphere, the plasma rotates in the same direction as that of

the Kerr black hole and never rotates against that direction. The magnetic field lines are tied to the rotating plasma (ideal MHD condition); therefore, the magnetic field lines are twisted azimuthally around the ergosphere, and the azimuthal component of the magnetic field increases. The magnetic field lines are strongly twisted (Fig. 1b), and the twist of the magnetic field line propagates outward as a torsional Alfvén wave. Similar effects (i.e., the generation and propagation of the torsional Alfvén wave) were also shown in cases of initially vertical, uniform magnetic fields around Kerr black holes (Koide et al. 2002; Koide 2003). The torsional Alfvén wave is generated by essentially the same mechanism as that of the rotating disk in the nonrelativistic cases (Blandford & Payne 1982; Uchida & Shibata 1985; Shibata & Uchida 1986; Ouyed, Pudritz, & Stone 1997; Meier, Koide, & Uchida 2001). In the present case, the plasma in the ergosphere plays the same role as that of the heavy disk in the nonrelativistic cases. The magnetic force of the twisted magnetic flux tube blows off the plasma outward at $t = 10.7\tau_s$ (Fig. 1b). The maximum velocity of the outflow is $0.86c$ at $t = 10.7\tau_s$, and the outflow is relativistic (the Lorentz factor is $\gamma = 2.0$). Such a distinct relativistic outflow has never been seen in the previous general relativistic MHD simulations with initial uniform vertical magnetic fields (Koide et al. 1998, 1999, 2000, 2002; Koide 2003). Numerical results with several other sets of parameters show that such a relativistic outflow from the Kerr black hole is formed only when the magnetic field is very strong ($B^2_0/\mu_0 \gg \rho_0 c^2$) and only when the black hole rotates very rapidly ($a \sim 1$).

To demonstrate this result more intuitively, we show in three dimensions the magnetospheric structure around the Kerr black hole at $t = 10.7\tau_s$ (Fig. 2). The tubes represent the magnetic field lines, and the arrows represent the plasma velocity. All magnetic tubes cross the ergosphere and are twisted strongly azimuthally as a result of the frame-dragging effect around the Kerr black hole. The magnetic flux tubes are shaped like propellers, and the rapidly rotating propellers blow off the plasma because the plasma does not cross the magnetic flux tubes (ideal MHD condition). The magnetic propellers are supported by the magnetic pressure and tension. The strongly twisted magnetic field lines also increase the magnetic tension so as to pinch the

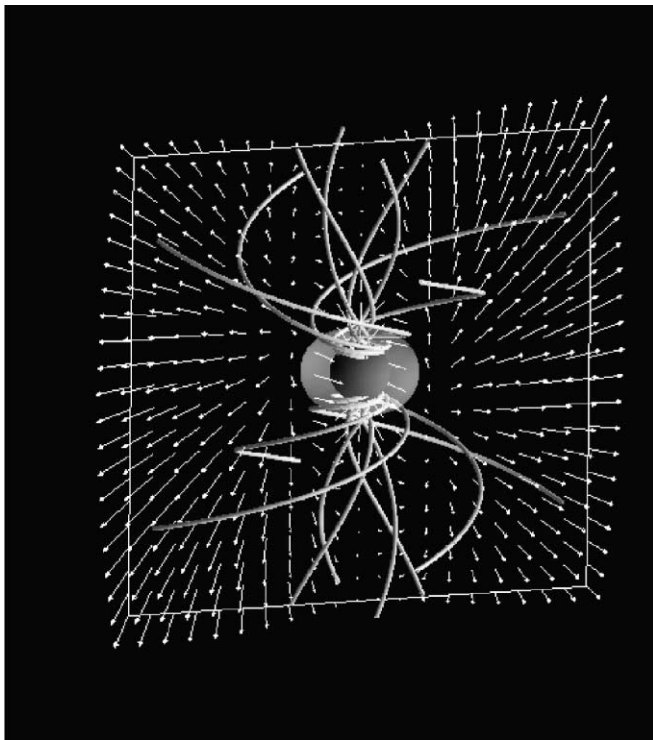


FIG. 2—Three-dimensional graphic of magnetic field lines and plasma flow around the Kerr black hole at $t = 10.7\tau_s$. The black sphere at the center depicts the black hole horizon. The transparent (gray) surface around the black hole is that of the ergosphere. The arrows show the plasma flow velocity. The tubes in the shape of propellers show the magnetic field lines. [See the electronic edition of the Journal for a color version of this figure.]

outflow of the plasma. The relativistic outflow is formed outside of the ergosphere, but it is not yet pinched strongly because of the short term of the present calculation.

To identify the acceleration mechanism of the plasma, we show the electromagnetic power and gas pressure power density for the plasma acceleration, $W_{EM} = \alpha \mathbf{v} \cdot (\rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B})$ and $W_{gp} = -\mathbf{v} \cdot \nabla(\alpha p)$, respectively, along the line $z = 2.19r_s$ at $t = 10.7\tau_s$ (Fig. 3). Here ρ_e is the electric charge density; $\mathbf{E}$ is the electric field; $\mathbf{J}$ is the electric current flux density; $\mathbf{B}$ is the magnetic field; $\rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B}$ is the density of the Lorentz force; and p is the gas pressure. Figure 3 clearly shows that the electromagnetic force predominately accelerates the plasma. We also evaluate the poloidal and azimuthal components of the electromagnetic power, $W_{EM}^{pol} = \alpha \mathbf{v}_p \cdot (\rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B})$ and $W_{EM}^\phi = \alpha \mathbf{v}_\phi \cdot (\rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B})$, where $\mathbf{v}_p$ and $\mathbf{v}_\phi$ are the poloidal and azimuthal components of the velocity, respectively. This indicates that the contribution of the magnetic pressure (W_{EM}^{pol}) for the outflow formation is almost twice of that of the magnetic tension (W_{EM}^ϕ), but the latter is not negligible. Therefore, the outflow is accelerated by both the magnetic pressure and the tension.

The numerical simulation presented here clearly shows that when the magnetic flux tube (in which the poloidal magnetic field is oblique to the black hole rotation axis and in which the magnetic energy dominates the rest-mass and internal energy of the plasma) crosses the ergosphere of the rapidly rotating black hole, it rotates like a propeller screw as a result of the frame-dragging effect of the black hole and propels the plasma outward near the black hole and toward the relativistic regime. This is the first distinct, self-consistent solution showing the possibility of a spontaneous relativistic outflow formation by a magnetic field around a rotating black hole. In previous calculations with an initially uniform, strong magnetic field, and thin plasma around a rapidly black hole, no outflow is found, while the strong energy is emitted from the ergosphere (Koide et al. 2002; Koide 2003). This shows the importance of the magnetic configuration around the black hole for relativistic jet formation. It is noted that the result shows a transitory phase and that the relativistic outflow is not collimated until $t = 10.7\tau_s$. After the long-term simulation, the pinch effect of the magnetic tension may make the outflow a relativistic jet. It is also noted that the density of the initial distribution of the plasma is assumed to depend on radius $\sim r^{-5}$. Such a high density gradient may also be required for relativistic outflow formation.

Here we discuss the possible application of this process of relativistic jet formation on the radial, strong magnetic field from the rapidly rotating black hole to the mechanism of the central engine of GRBs. Among the many models of the relativistic jet from the GRB engine, the model of the gravitational collapse of a large star ($M > 10 M_\odot$), which is called a “collapsar” or “hypernova” model, seems to be one of the most promising (Woosley 1993; Paczyński 1998). It is plausible that the large star had a strong magnetic field that was caused by the dynamo inside the star. During the collapse of the star and the formation of the black hole, the plasma of the star that is falling drags the magnetic field lines into the black hole that is forming. Most of the magnetic field lines may be swallowed by the black hole along with the fallen plasma. However, the radial magnetic field lines that are parallel to the plasma flow velocity will remain. The present numerical simulations indicate that the relativistic outflow may be ejected directly from the ergosphere along the magnetic field lines when the magnetic field is strong enough to dominate the plasma around the black

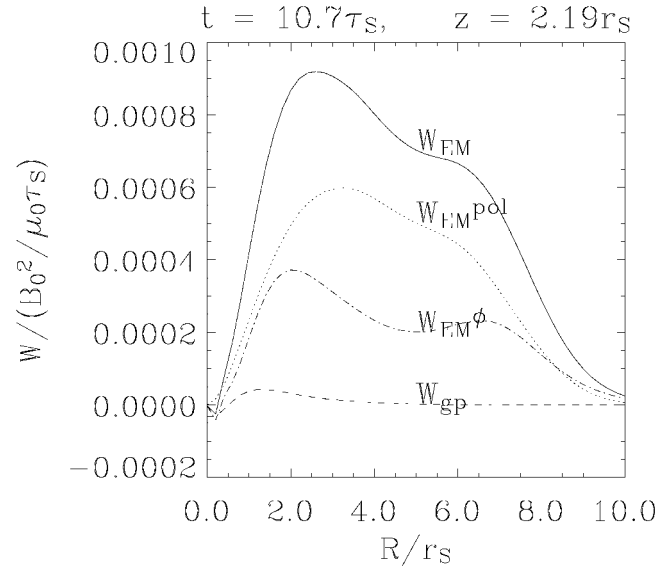


FIG. 3—Power density of the Lorentz force (W_{EM} , solid line) and the gas pressure gradient (W_{gp} , dashed line) to the plasma acceleration along the line $z = 2.19r_s$ at $t = 10.7\tau_s$. The poloidal and azimuthal components of the electromagnetic power (W_{EM}^{pol} , dotted line; W_{EM}^ϕ , dot-dashed line) are also shown. The former (latter) component, W_{EM}^{pol} (W_{EM}^ϕ), evaluates the contribution of the magnetic pressure (tension) for the outflow acceleration.

hole. The collimation of the jet is important in that it explains the energetics of GRBs. The mechanism will be investigated by a longer term simulation with various magnetic field configurations and more realistic plasma envelopments around the black hole based on a collapsar/hypernova model.

All previous magnetically driven models assumed a very high density rotating disk around the central Kerr black hole, and the plasma inside/outside of the disk is accelerated by the magnetic field, where the line of force is anchored at the disk. However, the terminal velocity of the jet caused by the magnetic field is comparable to the rotational velocity of the disk, in which the jet is launched, except for extremely strong magnetic field cases, in spite of the magnetic field strength (Kudoh, Matsumoto, & Shibata 1998). The velocity of the circularly rotating disk can be relativistic only when the disk rotates at the vicinity of the horizon (at least in the ergosphere) around the maximally rotating black hole ($a \sim 1$). The rotational velocity of the disk outside of the ergosphere is nonrelativistic, and the powerful energy supporting the energy source of the GRBs is not expected from the disk. In fact, the general relativistic MHD simulations of a magnetized disk around a rapidly rotating black hole show only subrelativistic jets, $v_{jet} < 0.5c$ (Koide et al. 1998, 1999, 2000). The present simulation confirms that the relativistic jet is spontaneously formed by the plasma in the ergosphere through the radial magnetic field without an actual rotating disk. The relativistic jet is much faster and more powerful than the jet from the disk outside of the ergosphere. In the present result, the collimation of the outflow is not found. After the long-term simulation, the relativistic outflow may be pinched by the magnetic tension of the strongly twisted magnetic field lines to become a jet, and its Lorentz factor will be much larger than the present one, $\gamma = 2.0$, after the magnetic energy is completely converted to kinetic energy.

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